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An ontology model to support the automated design of aquaponic grow beds

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Abstract

Aquaponics is a promising sustainable farming method that combines aquaculture and hydroponics. It allows the growth of crops without soil, pesticides, or fertilizers, and with a minimum amount of water. In aquaponic systems, the design of the growing area is directly linked to the type of crop about to be planted. The type of crop directly determines, for example, the spacing between plants and between channels, which is critical to determine the footprint required and estimate the system productivity. This paper proposes a knowledge modeling approach to support the design of aquaponic systems by automatically determining the required characteristics of the aquaponic system based on crop selection. The knowledge modeling is outlined as an ontology model that formally describes the existent links between the aquaponic grow bed characteristics and its design parameters. This study gives practitioners the capacity to visualize the impact of the desired crop selection on the aquaponic system design, as well as supporting clearer decision-making regarding production facility layout and system design in aquaponic farms.

Keywords: knowledge modeling; aquaponics; precision farming; parametric design; design automation

1. Introduction

Food security and sustainability have become a major concern over the years due to substantial urbanization, destruction of the ecological environment, farmlands scarcity, and increasing growth of the human population [1]. Traditional agriculture methods employed for crop production require vast amounts of land, time, and manpower and hence are not very efficient to meet the current food demands. Consequently, the current paradigm poses a need to explore new farming methods. Aquaponics, a subset of integrated agri-aquaculture systems, is expected to address these problems due to its ability to develop and achieve economically viable and environmentally sustainable food production practices [2]. The rationale of this soilless recirculating growing system involves sharing the mutual benefit of the available resources, such as water and nutrients, between aquaculture and plant production.

An aquaponic system is comprised of two integrated units: 1) a hydroponic unit which consists of grow beds for plant growth; and 2) an aquaculture unit that involves water tanks for fish habitat and biofilters for the breakdown of ammonia [3]. These units work together in a symbiotic environment to enable plant and fish growth. Primarily, depending on the structure of the plants' grow bed and crop type and size, there are three different types of aquaponics system designs: nutrient film technique (NFT), media bed, and deep water culture (DWC) [4]. In this paper, the NFT based aquaponic system is considered because it is the most popular type of aquaponic setup used. Moreover, it uses less water and is suitable to grow leafy green crops. In NFT systems, a very thin film of nutrient-rich water is pumped to enclosed channels. The top cover of the channel consists of circular or squared shaped pockets known as plant sites where plants sit in small plastic cups allowing their roots to access the water and absorb the nutrients [5].

The design and management of an NFT-based indoor aquaponic system present several challenges when scaling it to a commercial level [6]. These challenges are mainly attributable to the design of grow channels based on crop

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selection. Each crop has a certain width and height at optimal environmental conditions that impact the design infrastructure of the aquaponics system in terms of plant site spacing and distance between grow channels [7]. This in turn affects the system productivity which involves crop yields and product quality. Hence, to ensure high system productivity, the proper design and placement of grow channels are significant. To achieve this, the complex and heterogeneous existing links between grow bed design and crop characteristics need to be formally described by appropriately capturing the data and managing the knowledge related to these entities. In this essence, ontology is regarded as one of the normative knowledge modeling tools that provide semantic interoperability and a general understanding of specialized multidimensional knowledge in various domains that is cognitively transparent and accessible to human experts and software agents [8–10]. The ontology models, in combination with rule systems, act as strong candidates to construct a decision support platform for the representation of different knowledge sources and facilitation of knowledge-driven decisions in a reusable and modular manner [11].

So far, no attempt has been made towards knowledge modeling of the aquaponics system particularly for the representation of the grow bed design knowledge based on crop selection. Therefore, the purpose of this paper is, to provide a knowledge model in form of an ontology model to support the parametric design automation in an indoor aquaponics system with the notion to automatically determine the design parameters of grow bed based on the crop selection. This ontology model stores knowledge gathered from farm, domain experts and databases. The inferred knowledge is then extracted and used to calculate grow bed design parameters for specific crop. To streamline the decision-making process a graphical user interface (GUI) is developed. This research study allows aquaponics' practitioners to visualize the impact of crop selection on aquaponic system design, which eventually will facilitate in better decision making regarding crop production in aquaponic farms.

The paper is structured in 8 sections. Section 2 introduces a knowledge-based decision support framework for the parametric design automation of aquaponic grow beds based on crop selection. Section 3 provides the overview of the main classes of aquaponic ontology, namely, *AquaONT* and relationships between them. Governing equations devised to determine design features of grow bed are described in section 4. The user interface developed to visualize the behavior of *AquaONT* is presented in section 5. Section 6 presents use-case considering basil crop. The analysis of the results obtained in section 6 are covered in section 7. Finally, section 8 concludes the paper by addressing the efficacy of this study.

2. Decision support framework for automated design of aquaponic grow beds.

The effective decision making related to design of grow beds based on crop selection in aquaponic farms is contingent upon the representation, extraction, and usage of available knowledge about contributing entities. For this purpose, a decision support framework is proposed in this paper, the layout of which is shown in Fig.1.

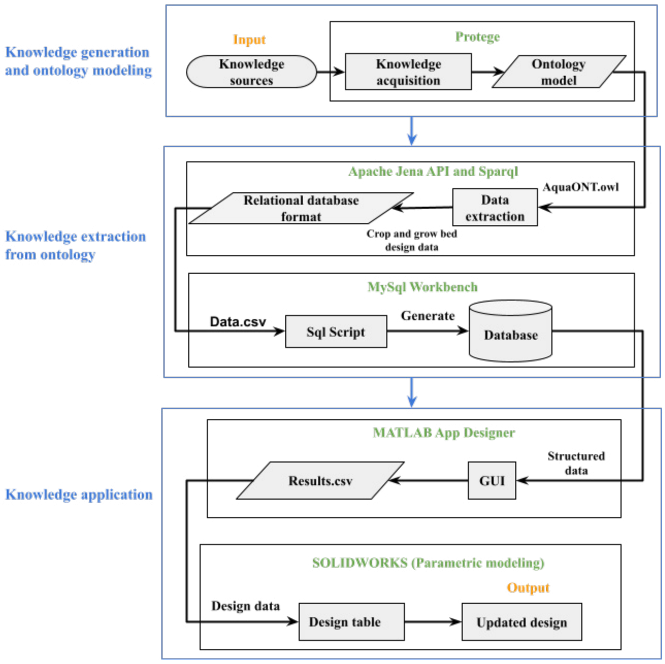

Fig. 1. Decision support framework for automated design of grow beds.

The proposed framework consisting of three primary stages depicts the complete lifecycle of decision making process based on knowledge extracted from ontology model. To represent the aquaponics knowledge, first, an ontology model is developed by acquiring knowledge from farm and domain experts and unify it as domain concepts. Then, the existing and inferred knowledge about crop characteristics and grow bed design features is extracted from the ontology model using Apache Jena API [1] and SPARQL query language. Then, MySQL Workbench[2], is used to import and organize extracted knowledge into a database. MATLAB database explorer toolbox is employed to link this database with the MATLAB app designer module which along with various mathematical equations are utilized to develop a graphical user interface (GUI). Finally, the results (design features) obtained from GUI are exported to SOLIDWORKS for parametric modeling of the final grow bed design.

3. AquaONT: an ontology model for aquaponic system

In this section, *AquaONT* is introduced, which is an OWL ontology developed to represent and model the essential knowledge of the aquaponics system. This ontology model is created in Protégé 5.5, which is an open-source ontology editor developed by Stanford University. First, the upper-level ontological knowledge model known as base ontology is presented that provides the domain-specific concepts related to the aquaponic system. Then, product and production system concepts are presented, that define the crop characteristics and grow bed features, respectively.

[1] https://jena.apache.org/tutorials/rdf_api.html

[2] https://www.mysql.com/products/workbench.

3.1. Upper level ontological knowledge model

An ontology model, O, represents the dimensions of domain-specific knowledge in terms of four fundamental elements referred to as a tuple: O = {C, I, OP, DP}, where the concept (C) is a set of instances, the instances (I) are the objects in the domain, the object property (OP) is the relationship between two concepts or instances, and the datatype property (DP) links instances with literal variables (integer or string) [12]. Fig.2 shows upper level ontological model of *AquaONT*, also known as the base ontology model. Six "classes" or "concepts" are created to represent the six knowledge domains. These concepts are related to each other through object properties, which are given in Table 1.

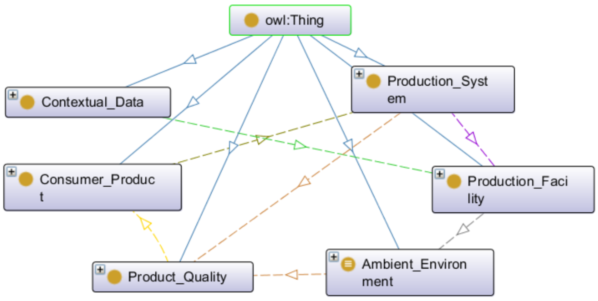

Fig. 2. Upper level ontological model of AquaONT

Table 1. Relationships between classes/concepts.

Domain	Object property	Range
Ambient_Environment, Production_System	have_Impact_on	Product_Quality
Production_Facility	is_Maintained_at	Ambient_Environment
Contextual_Data	is_Received_from	Production_Facility
Consumer_Product	is_Output_of	Production_System
Product_Quality	is_Characteristic_of	Consumer_Product
Production_System	is_Established_in	Production_Facility

The class Ambient_Environment specifies the optimal ranges of environmental parameters that ensure the healthy growth of crops and fishes in an indoor aquaponics system. These parameters are classified into two categories: 1) indoor environmental parameters which include water temperature, pH, electroconductivity, ammonia, dissolved oxygen, nitrate and nitrite level, water hardness, water level, water flowrate, alkalinity, salinity, air temperature, light intensity, humidity, and CO2; and 2) outdoor environmental parameters which involve the daily weather conditions, routine climatic changes, day-night times, and seasons.

The notion of product in any production system refers to the outcome of the process [13]. In an aquaponics system, there are two primary products: ready-to-harvest crops and fish. Consumer_Product class represents the product knowledge in terms of crop and fish type, crop and fish growth status, and crop and fish optimal growth parameters. A wide variety of crops can be grown in an aquaponic system, but each crop needs distinct environment to thrive, and has its own standard height and width at maturity stage or at the time of harvesting. These aspects are significant in determining the design of growbeds and therefore, are also represented under this class.

Besides biological components, an indoor aquaponics system consists of various mechanical and electrical components. Production_System class models the knowledge about these components under the subclasses digital system and mechanical system. The digital system is further categorized to include sensors, controllers, and other electronic or network devices. Whereas the mechanical system subclass represents design features of grow beds, fish tanks, and biofiltration tanks with respect to crop and fish type.

In an indoor aquaponic system, the idea is to control and maintain the optimal environmental conditions to enhance the crop yields, for which location of the system plays a significant role. Production_Facility class, therefore, specifies the location where the aquaponics system is located and managed. This class also represents the workers that are responsible for managing each part of the aquaponics system through a centralized system.

For remote monitoring and control of the aquaponic system, context information is obtained from sensors through proper connectivity channels and is utilized to enable data-driven decisions in the knowledge model. This context information is related to real-time data of surrounding conditions in aquaponics farms and is therefore represented under the class Contextual_Data.

The Product_Quality concept models the product qualitative aspects, quality control standards, and quality assessment criteria and links these attributes with the knowledge represented for a consumer product, production system, and ambient environment covered in previous concepts.

To verify *AquaONT*, Protégé built-in reasoner, HermiT was used. The computation was done successfully without errors, showing the accuracy of ontology. Similarly, to validate ontology, Sparql queries were developed and executed. Every time, these queries produce the same results for the given conditions, representing the consistency and coherence of ontology.

3.2. Consumer product and production system concepts

Ontologies enable the interoperability of autonomous agents and support the design of production systems [14]. In this study, *AquaONT* is used to enable parametric design automation – involving determination of design features of aquaponic grow beds pertaining to each crop. To achieve this, two concepts, namely, Consumer_Product and Production_System are employed and extended to include several sub-concepts which are then populated with the knowledge of grow bed design features and crop characteristics gathered from domain experts and farm. The detailed hierarchical architecture of these two concepts along with significant sub-concepts and instances is shown in Fig. 3.

The different types of crops are defined as instances (Icrop) under the sub-concept Crop_Type. The crops considered in this study are leafy green vegetables: basil, chard, lettuce, parsley, and spinach. The characteristics of these crops involve standard plant spacing (PS), width (Wi), and height (H) as recommended by aquaponics professionals. PS is defined as the distance between two consecutive plants on the same channel. These characteristics are the attributes of respective crop represented as literals and linked with instances through corresponding datatype properties: "hasPlantSpacing", "hasPlantWidth", and "hasPlantHeight" respectively.

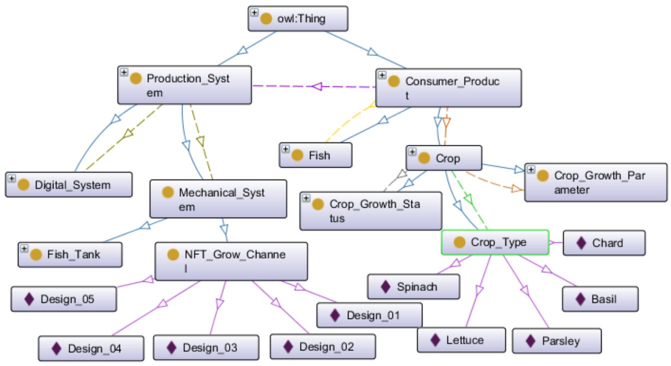

Fig. 3. Architecture of Consumer_Product and Production_System class.

Likewise, the design parameters of the grow channels are modeled under the instances (Idesign) of the sub-concept NFT_Grow_Channel. These instances represent different design categories, and each category specifies a certain width (W), length (L), depth (D), plant site spacing (S), plant site size (SS), vertical channel spacing (VCS), and horizontal channel spacing (HCS) of a NFT grow system. These parameters are the attributes represented as literals and linked with the design categories through datatype properties "hasWidth", "hasLength", "hasDepth", "hasPlantSiteSpacing", "hasPlantSiteSize", "hasVerticalChannelSpacing", and "hasHorizontalChannelSpacing" respectively. Fig. 4 shows the crops' basic dimensional characteristics and generalized design features of a NFT grow channel.

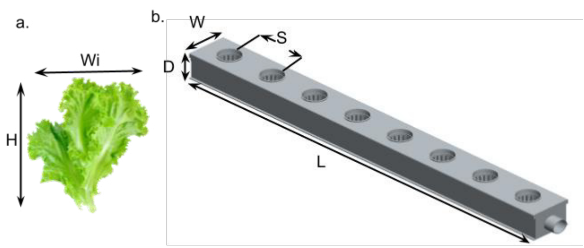

Fig. 4. a) Crop characteristics; b) Grow channel design features

4. Calculation of grow bed design parameters

Using the attributes specified for instances of sub-concepts-crop type and NFT grow channel given in section 5 - equations are developed to calculate design parameters of grow bed. For instance, PS and L are used to determine the number of plant sites per channel (NPSC). NPSC is defined as the capacity of each channel to grow number of plants. In Fig. 4b, NPSC is 8, which implies that in this particular channel, only 8 plants can be grown. The S on the grow channel is directly related to PS and is essentially important to ensure high crop yields. Other yield parameters that are impacted by PS in the aquaponic system are plant height, leaf area, and leaf number. The general rule of thumb in this essence is to build plant sites on each channel and keep the spacing of channels according to the expected width of the plant at its maturity stage [15]. NPSC along with the total number of channels (NC) needed to build the complete hydroponic unit determines the production capacity (PC) of the aquaponic system, which is equivalent to the maximum possible crop yield. Equations (1) and (2) are developed for computing NPSC and PC, respectively.

$$NPSC = {}^{L}/_{S} \tag{1}$$

$$PC = NPSC \times NC \tag{2}$$

The grow channels can be stacked horizontally or vertically or both by maintaining the recommended HCS and VCS. Moreover, the farm space must also be taken into consideration while choosing NC and respective stacking setup. With horizontally stacked NFT channels, the length of the fully developed hydroponic unit is the same as the length of the grow channel, L, whereas the width of (WHU) is equivalent to the sum of widths of all channels and horizontal spacings between channels. Equation (3) is formulated to determine WHU.

$$WHU = (NC \times W) + ((NC - 1) \times HCS) \tag{3}$$

Another significant agronomic factor that enhances the crop yield is plant density or plant population (PD). PD measures the number of plants per unit area and its optimum value varies with the genotype and geographic location [16]. In aquaponic systems, the number of plants to be grown refers to the production capacity of the system, whereas the unit area is related to the area of hydroponic component. To compute PD, Equation 4 is devised.

$$PD = {}^{PC}/_{(L \times WHU)} \tag{4}$$

These equations use the existing and inferred knowledge from *AquaONT* to determine mentioned design features and to visualize this, GUI is developed which is explained in the next section.

5. AquaONT application: Graphical User Interface

To visualize the behavior of *AquaONT*, a GUI is developed using MATLAB app designer tool which is shown in Fig.5. This GUI uses inferred knowledge from *AquaONT*, and equations developed in section 4. It allows users to make a crop and a channel length selection and observe the impact on design parameters in terms of numerical value. For better visualization of design variations in the grow channel as a 3D CAD model, these numeric values are sent to SOLIDWORKS, where they are applied to the already built design referred to as default parametric design.

Five fields are created on the GUI to represent the knowledge of the ontology model: *1) Crop Field, 2) Grow Bed Design Field, 3) Environmental Parameters, 4) NFT Channel Selection, and 5) NFT based Crop Production System*. First four fields are populated with existing and inferred knowledge from *AquaONT* - acquired directly through SQL database, whereas the last field is linked with the set of equations created in section 4. The *Crop Field* describes the five leafy green crops along with their characteristics such as H, Wi, and PS [17]. The *Grow Bed Design Field* gives information about the grow bed type, PS, HCS, and VCS of each crop. The *Environmental Parameters* field specifies the optimal growth conditions for these crops. The entries of field 2 and 3 are auto-populated once the crop is selected. For the selection of the right NFT channel, the *NFT Channel Selection* field is incorporated, where length of channel is the deciding factor. The channel lengths considered are 6 feet, 8 feet, 10 feet, and 12 feet.

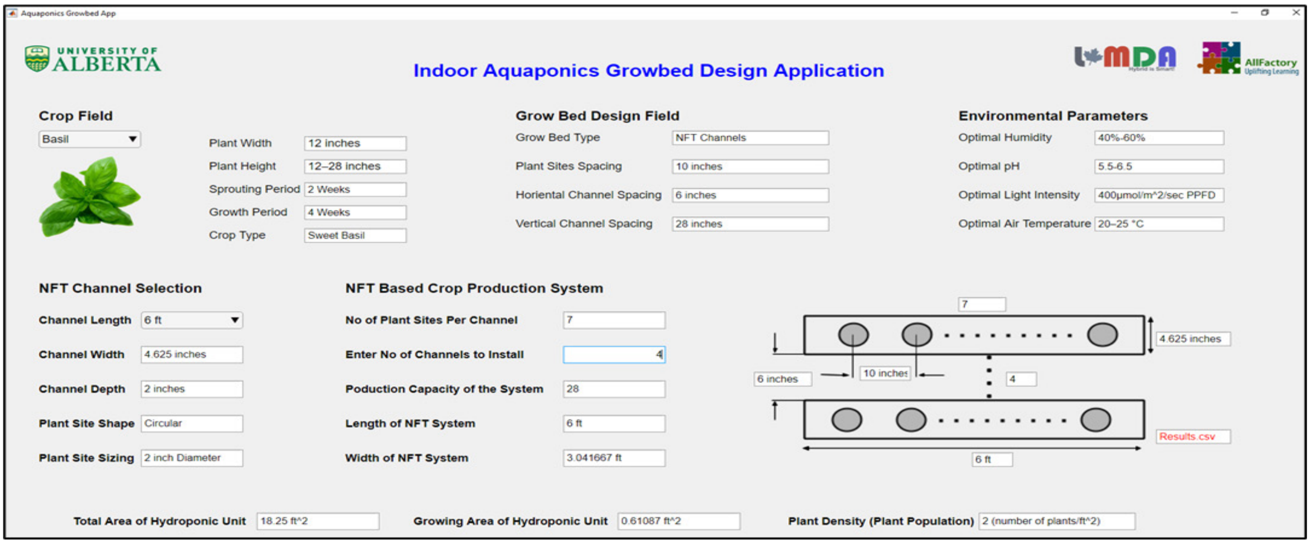

Fig. 5. Graphical User Interface for AquaONT design application developed by LIMDA, University of Alberta.

The other parameters under this field such as width and depth of the channel are kept constant for the sake of simplifying the model. Moreover, the shape of plant site is chosen to be circular with diameter of 2 inches. The plant site can also be squared shape. The last field on the GUI is the *NFT based Crop Production System*. This field uses entries of previous fields and governing equations given in section 4 in order to calculate parameters. This field is important as it gives information about the production capacity of the system along with the length and width of the complete hydroponic unit once the user selects the number of channels. In addition, three auxiliary fields are created at the lower side of the GUI window, which displays the total area of the hydroponic unit, total growing area, and plant density (plant population).

6. Use Case – Grow bed design for basil crop

The use-case presented here aims to illustrate the feasibility of *AquaONT* and GUI. For this purpose, basil crop is considered, which is one of the most common economically viable products in aquaponic systems. The optimal environmental conditions to grow basil in indoor farms, standard height, and width under these conditions, and HCS, VCS and PS are shown in Fig. 5. These values are extracted from *AquaONT*. Assuming the user selects 6 feet long NFT channel for its aquaponic system and his/her farm can accommodate a maximum of four channels. After entering these values in the relevant fields in GUI, the design parameters under the fifth field are automatically calculated. For the given inputs such as L = 6ft and NC = 4, the results show that only 7 basil plants per channel can be grown and these plants must be placed 10 inches apart on each channel. In addition, each channel must be placed at a distance of 6 inches from each other. The application also calculates total area, the effective growing area, and the PD of the hydroponic unit which in case of basil are: 18.25 ft^2, 0.61ft^2, and 2/$ft^{2,}$ respectively, see Fig.5.

Finally, to visualize the CAD model of NFT grow system for basil, the calculated design parameters from MATLAB are imported in SOLIDWORKS. These parameters are saved in a design table which enables parametric modeling. The idea is to develop a default design of a grow system in CAD software and automatically update it with a single click without designing the entire part or assembly again by using the new design details stored in design table. This process is showcased by presenting the basic case of basil crop. The default and updated grow channel design for basil is shown in Fig. 6. Before implementing the parameters saved in design table, L = 96in with NPSC = 8 for default design but after application, L becomes 72in with NPSC reduced to 7 – showing the updated design configuration for basil. The process is repeated for basil, lettuce, and parsley for different input values. The results obtained are explained in next section.

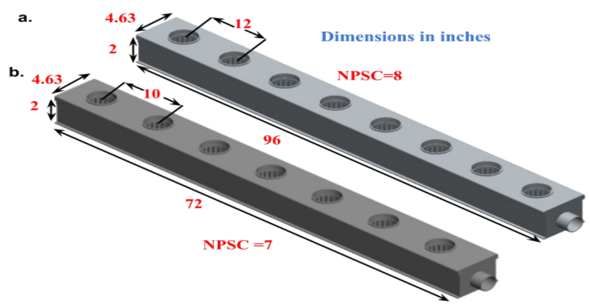

Fig. 6. a) Default grow bed design. b) Updated grow bed design for basil.

7. Results and discussion

The proposed system is simulated for all the crops mentioned in section 3.2. Fig.7 shows the design configurations of hydroponic unit for three crops with two different input sets – including {L, NC} = {72in, 4} and {96in, 6}. The results show that for same channel length, NPSC is different for each crop. This is due to the distinct requirement of plant site spacing (S) for each crop such as $\{S_{basil}, S_{lettuce}, S_{parsley}\} = \{10,8,12\}$. Similarly, the production capacity of the hydroponic unit is also different for each crop. For the same NC, it is observed that the PC of the system for lettuce is 22.22% and 33.33% higher than for basil and parsley, respectively. If L is increased from 72in to 96in and NC is increased from 4 to 6, the resulting NPSC and PC will also be increased. For instance, in Fig. 7 (e, f) NPSC and PC for parsley are increased from 6 and 24 to 8 and 48, respectively. With these visualization results in place, crop

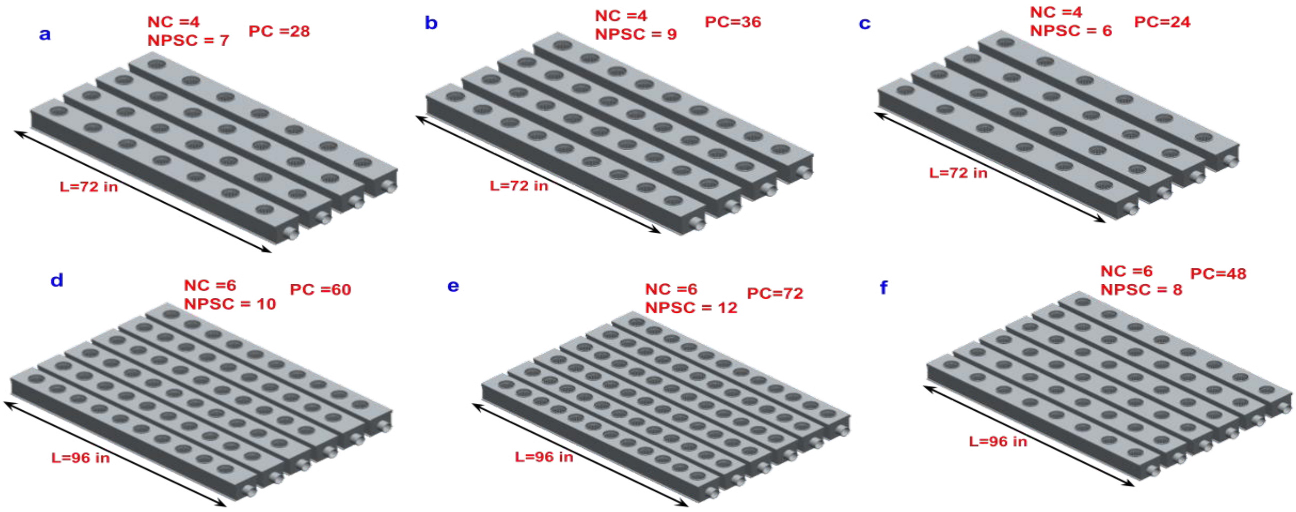

Fig. 7. NFT grow bed design configurations for different crops: (a, d) Basil; (b, e) Lettuce; (c, f) Parsley

characteristics such as PS, Wi, and H significantly impact the design parameters of grow channel in an aquaponic system. Having a correct grow bed design in aquaponics system for crop growth is crucial because it ensures high yields. Moreover, it also ensures the right amount of water and nutrient absorptions, that eventually leads to high crop quality with right nutritional value. In this essence, a quick knowledge-based virtual tool assists in decision making related to the proper design of grow bed based on crop characteristics.

For future work, intelligent techniques such as machine learning, deep learning, and computer vision will be incorporated to make the system smart and autonomous. Moreover, a cost model will also be integrated to optimize the aquaponic grow beds based on market demand.

8. Conclusions

Aiming at providing a knowledge-based system for automated decision-making regarding crop production and respective grow bed design in aquaponics farms, this paper has proposed a decision support framework. An ontology model, *AquaONT,* is developed to assist in decision making process, which can be extended to include other elements and tested against robust case studies. GUI is developed that uses inferred and existing knowledge from *AquaONT* and mathematical equations to calculate design parameters. To visualize the impact of crop selection on the design of grow beds, parametric modeling is performed. The analysis of results shows that the correct design of grow bed ensures high crop yield and quality.

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